REVIEW ARTICLE

Sahjan (Moringa oleifera): Phytochemistry, pharmacological effects, and therapeutic applications –A comprehensive review

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Abstract

Moringa oleifera, commonly known as Sahjan or the drumstick tree, is widely recognized for its nutritional richness and medicinal value. In recent years, it has gained significant attention due to its diverse bioactive compounds, including flavonoids, phenolics, and glucosinolates, which contribute to its therapeutic potential. This review provides an updated overview of the phytochemistry, pharmacological activities, and therapeutic applications of *M. oleifera*. Studies have reported its antioxidant, anti-inflammatory, ant diabetic, antimicrobial, and anticancer properties, largely mediated through key molecular pathways. Although preclinical findings are promising, clinical evidence remains limited, and issues related to standardization and safety need further investigation. Overall, *M. oleifera* holds strong potential as a natural therapeutic agent and functional food, warranting more focused research for its effective clinical application.

Key words: Bioactive compounds, molecular pathways, *Moringa oleifera*, pharmacological activities, phytochemistry

INTRODUCTION

The emergence of antibiotic resistance has renewed interest in natural antimicrobial compounds, with *Moringa oleifera* showing particular promise due to its traditional medicinal applications. This study evaluated the anti-bacterial efficacy, phytochemical composition, and cytotoxicity of various *M. oleifera* extracts (seeds, flowers, leaves, and resin) using ethanol, acetone, and methanol as solvents. The anti-bacterial activity was assessed against six bacterial strains using the agar disc diffusion method. The ethanol extract of resin demonstrated exceptional anti-bacterial activity against Streptococcus mutans, achieving 76.2% effectiveness compared to the positive control. Gas chromatography–mass spectrometry (GC-MS) analysis identified hydroquinone (38.46%) as the predominant compound in resin extract and benzeneacetonitrile, 4-hydroxy- (37.35%) in seed extract. Cytotoxicity testing using zebrafish embryos revealed favorable safety profiles with median lethal concentration (LC_{50}) values of 416 mg for resin extract and 293 mg for seed extract. In addition, larvicidal and ovicidal assessments showed significant vector control potential, with resin extract demonstrating superior efficacy (LC_{50} = 451.62 ppm) compared to seed extract (LC_{50} = 485.99 ppm). The findings suggest that *M. oleifera* extracts, particularly from resin and seeds, possess promising anti-bacterial properties with a favorable efficacy-to-toxicity ratio, warranting further investigation for potential therapeutic applications.

BOTANICAL DESCRIPTION AND DISTRIBUTION

M. oleifera Lam. belongs to the family Moringaceae, which comprises a single genus with 13 species distributed across Asia, Africa, and Madagascar.[1] It is a fast-growing, tropical, deciduous perennial tree characterized by a soft, brittle stem with whitish-gray bark and drooping branches. The leaves are compound, typically tripinnate, with small, ovate leaflets, while the flowers are creamy-white and fragrant. The plant produces elongated, pendulous pods containing round seeds with wing-like structures.[2]

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M. oleifera is native to the sub-Himalayan regions of northern India but is now widely cultivated throughout tropical and subtropical regions of the world, including Asia, Africa, and Latin America.[3] The plant adapts well to a variety of environmental conditions and grows optimally at temperatures between 25°C and 35°C under direct sunlight, in well-drained soils with pH ranging from 5.0 to 9.0.[4] It is highly drought-tolerant and can survive in poor soil conditions, making it suitable for cultivation in arid and semi-arid regions.

The plant can be propagated through seeds or stem cuttings, with vegetative propagation preferred for uniformity. *M. oleifera* begins bearing fruits within 6–8 months of planting, and yield improves significantly with age. India is the largest producer of *M. oleifera*, with major cultivation in states such as Andhra Pradesh, Karnataka, and Tamil Nadu. The plant is valued for its high productivity, with significant yields of pods and seeds, and its wide range of nutritional, medicinal, and industrial applications.[5]

PHYTOCHEMISTRY OF *M. OLEIFERA*

M. oleifera is a plant known for its rich phytochemical composition. It contains various bioactive compounds distributed across different plant parts. Various plant parts, including leaves, seeds, pods, roots, and flowers, contain a wide range of bioactive compounds.[6] A diverse range of over 90 phytochemical constituents has been reported in the genus *Moringa*, contributing to its broad spectrum of therapeutic properties. These bioactive compounds encompass proteins, amino acids, phenolic acids, carotenoids, alkaloids, glucosinolates, flavonoids, sterols, terpenes, tannins, saponins, fatty acids, glycosides, and polysaccharides.[7] *M. oleifera* seeds are rich in oil (43.56%), predominantly composed of unsaturated fatty acids, with oleic acid as the major constituent, followed by palmitic, stearic, lauric, linoleic, and linolenic acids. In addition, the seeds contain significant levels of polyphenols, flavonoids, and proanthocyanidins. Both seeds and leaves are abundant in flavonoids such as quercetin, rutin, kaempferol, myricetin, and isorhamnetin, as well as phenolic acids including gallic, caffeic, *p*-coumaric, and ellagic acids, contributing to their notable biological activities.[8] Immature pods and flowers of *M. oleifera* contain higher levels of monounsaturated fatty acids (16–30%) and relatively lower amounts of polyunsaturated fatty acids (34–47%) compared to the leaves.[5] *M. oleifera* leaves are a good source of vitamins, especially vitamin C, and fresh leaves have been reported to contain higher amounts than common sources like oranges.[9] The phytochemical composition of *M. oleifera* encompasses a broad spectrum of primary and secondary metabolites, including amino acids, vitamins, minerals, flavonoids, isothiocyanates, phenolic acids, and other bioactive constituents responsible for its biological activities.[10]

Flavonoid

Moringa exhibits strong antioxidant activity, primarily attributed to its high flavonoid content. These flavonoids are predominantly present in flavanol and glycoside forms. The other phytochemicals are rutin, quercetin, rhamnetin, kaempferol, apigenin, and myricetin.[11] Both leaves and seeds of *M. oleifera* are rich sources of flavonoids, including myricetin, rutin, kaempferol, quercetin, isorhamnetin, procyanidin, and catecholamine, and lutein pigments.[7] These compounds display significant antidiabetic activity by modulating key enzymes involved in glucose metabolism and improving insulin sensitivity. These enzymes regulate oxidative stress and inflammation, thereby contributing to the prevention and management of metabolic disorders. These also possess therapeutic potential in diabetes management.[12]

Alkaloids

Alkaloids are a class of basic nitrogen-containing compounds in which the nitrogen atom is typically present in the form of primary, secondary, or tertiary amines. Owing to their diverse pharmacological activities, these compounds hold considerable therapeutic significance. In *M. oleifera*, various alkaloids have been identified in different plant parts. The leaves contain alkaloidal constituents, while two novel alkaloids, marumoside A and marumoside B, along with aurnatiamide acetate, have been isolated from the roots.[13-15] Furthermore, the stem has been reported to possess moringinine and other moringin-type alkaloids.[7] Two novel pyrrole alkaloid glycosides, marumoside A and marumoside B, have been isolated from the leaves of *M. oleifera*, along with another related compound, pyrrolemarumine-4″-O-α-L-rhamnopyranoside.[11] A diverse range of alkaloidal compounds has been identified, including marumoside A[16] and B,[17] aurantiamide acetate, hostine D, methyl 4-(α-L-rhamnopyranosyloxy) benzylcarbamate, various pyrrolemorine derivatives (A–G), pyrrolemarumine, and tangutorids E and F.[18] Notably, pyrrolemorine A and pyrrolemorine E exhibited significant neuroprotective activity, effectively reducing PC12 cell damage induced by oxygen–glucose deprivation even at a low concentration of 0.1 μM.[10] The phytochemical composition and biological significance of major plant parts of Moringa oleifera are summarized in Table 1.

Phenolic Acid

Phenolic acids in *M. oleifera* constitute an important class of bioactive compounds that contribute significantly to its antioxidant, anti-inflammatory, and therapeutic properties.[19] The major phenolic acids identified in *M. oleifera* include chlorogenic acid, caffeic acid, gallic acid, and *p*-coumaric acid, which are known to play a key role in its antioxidant and disease-preventive activities.[1] Niazirin has been isolated

Table 1: Phytochemical composition and biological significance of major plant parts of *Moringa oleifera*

Plant part	Major phytochemicals	Key compounds	Biological significance
Leaves	Flavonoids, phenolics, vitamins, carotenoids	Quercetin, kaempferol, chlorogenic acid	Antioxidant, antimicrobial
Seeds	Glucosinolates, isothiocyanates, fatty acids	Benzyl isothiocyanate	Antimicrobial, anti-inflammatory
Pods	Phenolics, vitamins	Phenolic acids	Nutritional, antioxidant
Roots	Alkaloids, glycosides	Spirochin (reported alkaloid)	Pharmacological activity
Bark	Tannins, alkaloids		Anti-inflammatory, antimicrobial
Flowers	Flavonoids, nectar compounds	Kaempferol	Antioxidant

from the seeds and leaves of *M. oleifera* through ethanol and butanol extraction and has shown α-glucosidase inhibitory activity with an half-maximal inhibitory concentration (IC_{50}) value of 382.2 µM.[20] In addition, several phenolic compounds, including various caffeoylquinic acid derivatives, chlorogenic acid, benzoic acid derivatives, and methyl caffeoylquinates, have been obtained from leaf extracts using ethyl acetate and butanol. Other phenolics identified from different plant parts include caffeic acid, gallic acid, *p*-coumaric acid, and vanillin. Notably, cryptochlorogenic acid has also been reported and exhibits significant anticancer activity against Michigan Cancer Foundation-7 cells with an IC_{50} value of 20.8 µM.[10]

Amino Acids

M. oleifera is a nutrient-rich plant containing over 90 essential chemical constituents, including proteins, lipids, carbohydrates, and dietary fiber. Proteins are the most abundant component, constituting nearly 25% of the dry weight and comprising a wide range of essential and non-essential amino acids.[2] The seeds are particularly rich in lipids, accounting for about 30% of their dry weight, with major fatty acids such as oleic, palmitic, and stearic acids.[21] In contrast, the leaves contain significant amounts of lipid molecules, including palmitic and linolenic acids, further contributing to their high nutritional value. Overall, the rich nutrient profile of *M. oleifera*, especially its dried leaves, highlights its importance as a valuable dietary resource.[7]

Glucosinolate

Glucosinolates are an important class of sulfur-containing secondary metabolites in *M. oleifera* that contribute significantly to its pharmacological properties, including antioxidant, anti-inflammatory, and anticancer activities.[22] Glucosinolate compounds in *M. oleifera* are mainly isolated from ethanol extracts of the seeds and include bioactive constituents such as benzyl glucosinolates, moringasides (C–G), moringin, niazimicin, and glucomoringin. These compounds exhibit diverse biological activities, including α-glucosidase inhibition (moringaside E), anti-adipogenic and anticancer effects (moringin), and anti-allergic as well as antiviral properties (glucomoringin).[23]

Fatty Acids

Fatty acid compounds in *M. oleifera* have been identified from ethanol, methanol, and ethyl acetate extracts of leaves, seeds, and flowers. These include glycerol-1-(9-octadecanoate), heneicosanoic acid, monoacetyl glycerol, monacosan-15-one, octacosanol, oleic acid, 3,4-methyleneazelaic acid, and triolein.[24] Among these, oleic acid has demonstrated notable anti-allergic activity by inhibiting β-hexosaminidase and histamine release, with IC_{50} values of 53.76 µM and 56.05 µM, respectively.[25]

Sterols

Sterols constitute a pharmacologically significant class of phytochemicals distributed across all parts of *M. oleifera*, where they contribute to the plant's well-documented anti-inflammatory, antioxidant, and cholesterol-modulating bioactivities.[7] All parts of *M. oleifera* contain sterol compounds, isolable from methanol, ethanol, ethyl acetate, and acetone extracts. Five sterols have been identified across various plant parts: β-sitosterone, stigmasterol, β-sitosterol-3-O-glucoside, β-sitosteryl oleate, and 24-methylene-9,19-cyclolanostan-3-ol. Among these, stigmasterol and β-sitosterol-3-O-glucoside demonstrate notable anti-allergic activity, inhibiting β-hexosaminidase and histamine release with IC_{50} values of 75.92 and 38.27 µM, respectively; the compound selectively inhibits β-hexosaminidase release (IC_{50} = 24.93 µM). Stigmasterol exhibits multiple bioactivities, including anti-inflammatory effects through inhibition of caspase-1 and nuclear factor kappa B (NF-κB). It also shows anti-adipogenic activity by suppressing reactive oxygen species (ROS) production and arresting the cell cycle at the S and G2/M phases. Additionally, it enhances glucose uptake.[26,10]

Vitamins and Minerals

M. oleifera is an exceptionally rich source of essential vitamins and minerals, distributed across its leaves, seeds, and pods in concentrations that rival or surpass conventional dietary sources. The leaves and seeds contain appreciable amounts of essential minerals, vitamins, amino acids, and fatty acids,

including micronutrients such as iron, magnesium, and folate, alongside B-complex vitamins and vitamins A, C, and E.[27] The most predominant minerals – calcium, potassium, iron, and zinc – are essential for numerous physiological functions; notably, the calcium content of *M. oleifera* leaves surpasses that of conventional plant-based sources, supporting bone strength, hormonal secretion, and nerve transmission.[28] Dried leaves concentrate calcium, magnesium, phosphorus, potassium, copper, and iron at higher levels than fresh leaves, whereas fresh leaves retain superior vitamin C and E content.[29] Vitamins, including ascorbic acid, riboflavin, nicotinic acid, thiamine, and β-carotene, are consistently identified across extracts, complementing this broad mineral profile.[27] Collectively, this micronutrient density positions *M. oleifera* as a high-value nutritional intervention, particularly in populations vulnerable to micronutrient deficiency.

Isothiocyanates

Isothiocyanates are sulfur-containing compounds that exert well-documented anticancer activity in *M. oleifera* through dual mechanistic action. These compounds suppress carcinogenesis by inducing Phase II detoxification enzymes that neutralize and eliminate reactive carcinogens before DNA damage occurs, while simultaneously enhancing hepatic detoxification capacity to accelerate systemic toxin clearance.[27] The predominant isothiocyanate in *M. oleifera*, 4-(α-L-rhamnosyloxy)benzyl isothiocyanate (MIC-1), exerts anticancer activity through multi-target pathway modulation, inhibiting cancer cell proliferation, promoting apoptosis, and suppressing metastasis with minimal toxicity to normal cells.[30] At the molecular level, these effects are mediated through Bcl-2/Bax modulation, caspase activation, and ROSs generation, with demonstrated broad-spectrum activity across breast, colorectal, liver, and lung cancers.[31]

PHRMACOLOGICAL ACTIVITIES

M. oleifera elaborates a chemically diverse array of bioactive compounds across its tissues that collectively mediate a remarkably broad spectrum of pharmacological activities. Pharmacological studies confirm the hepatoprotective, cardioprotective, anti-inflammatory, antidiabetic, and anticancer potential of *M. oleifera*, alongside its ethnomedicinal applications in wound healing, pain, ulcers, and liver disease.[32] The pharmacological properties of *M. oleifera* have been studied across multiple biological domains, including cardioprotective, antioxidative, antiviral, antibacterial, antidiabetic, and anticarcinogenic effects, underpinned by exceptional bioactive compounds such as polyphenols.[33] Collectively, these activities engage molecular targets across metabolic, antimicrobial, anti-inflammatory, oncological, and cytoprotective domains, establishing *M. oleifera* as one of the most pharmacologically versatile medicinal plants in contemporary literature.[7]

Anticancer Activity

M. oleifera has emerged as a pharmacologically significant source of anticancer compounds, demonstrating broad-spectrum cytotoxic activity across multiple malignancy types through mechanistically diverse pathways. Its bioactive phytochemicals – including isothiocyanates, flavonoids, phenolic acids, and alkaloids – exhibit antioxidant, anti-inflammatory, apoptotic, and antiproliferative effects, with documented activity against breast, colorectal, liver, lung, prostate, and oral cancers.[31] Isothiocyanates from *M. oleifera*, particularly the predominant compound MIC-1, inhibit cancer proliferation and promote apoptosis through multiple signaling pathways, curbing migration and metastasis while exerting minimal adverse effects on normal cells.[30]

MITC quinazolinone derivatives synthesised from *M. oleifera* isothiocyanate significantly inhibit glioma U251, melanoma A375, colorectal HCT-116, cervical HeLa, and breast MDA-MB-231 cell proliferation in a time- and dose-dependent manner, increasing the Bax/Bcl-2 ratio and caspase-3 expression without toxicity to normal gastric mucosal cells.[34] *M. oleifera* contains an abundance of anticancer phytochemicals across its leaves, pods, and seeds – including glucosinolates, isothiocyanates, niazimicin, kaempferol, quercetin, and zeatin – that collectively confer its chemopreventive and chemotherapeutic properties.[35] Leaf and bark extracts of *M. oleifera* tested against MDA-MB-231 and HCT-8 cancer cell lines demonstrate a 70–90% reduction in colony formation and cell motility, a sevenfold increase in apoptotic cells, and 2–3 fold G2/M phase enrichment – effects attributable to eugenol, isopropyl isothiocyanate, D-allose, and hexadecanoic acid ethyl ester identified by GC-MS analysis.[36] Collectively, the mechanistic diversity, multi-target pathway engagement, and favorable safety profile of *M. oleifera* phytochemicals position this plant as a compelling candidate for further clinical investigation as an adjunct in integrative oncology.[31]

Antimicrobial and Antifungal Activity

The antimicrobial activity of *M. oleifera* is attributable to structurally distinct bioactive compounds distributed across its plant parts. N-benzyl, Sethyl thio formate, an aglycone of deoxyniazimincin isolated from the ethanolic root extract, confers broad-spectrum antimicrobial and antifungal activity against an extensive range of pathogens,[37] while methanolic leaf extract demonstrates targeted inhibition of urinary tract pathogens – including both Gram-negative organisms such as *Klebsiella pneumoniae* and *Escherichia coli*, and Gram-positive species including *Staphylococcus aureus* and *Staphylococcus saprophyticus*.[32,38]

M. oleifera demonstrates broad-spectrum antimicrobial and antifungal activity mediated by structurally diverse bioactive compounds distributed across its roots, leaves, seeds, stems,

and fruits. N-benzylethylthioformate, the aglycone derivative of deoxyniazimincin isolated from the alcoholic root extract, exhibits potent antimicrobial and antifungal activity against numerous pathogens, positioning it as a viable candidate for combating microbial resistance.[37] Methanolic leaf extract effectively inhibits urinary tract pathogens, including *K. pneumoniae, S. aureus, E. coli,* and *S. saprophyticus,* demonstrating activity against both Gram-negative and Gram-positive organisms.[39] Extracts derived from leaves, seeds, and stems exhibit broad antifungal efficacy against clinically and agriculturally significant fungal species, including *Aspergillus flavus, Aspergillus niger, Fusarium solani, Trichophyton mentagrophytes, Penicillium sclerotigenum, Cladosporium cladosporioides*, and *Rhizoctonia solani*, among others.[37] Notably, methanolic leaf extract achieves 99% suppression of *Botrytis cinerea*, a destructive necrotrophic plant pathogen, underscoring its phytoprotective potential. The antibacterial activity of *M. oleifera* seeds is primarily attributed to MIC-1, while leaf juice demonstrates broad anti-pathogenic capacity against multiple human-infecting microorganisms.[39] Alkaloids, flavonoids, and steroids present in *M. oleifera* fruits inhibit *Candida albicans* proliferation through protein denaturation and suppression of spore germination, mediated by the unique structural configuration of their steroid rings.[40] Seed kernel extract demonstrates selective potency against *Aspergillus* species, *Mucor, Bacillus cereus*, and *S. aureus*, with comparatively reduced efficacy against *Pseudomonas aeruginosa* and *E. coli*. The apolar seed extract exhibits antibacterial activity selectively directed against Gram-positive bacterial strains, indicating that extract polarity critically determines the spectrum of antimicrobial activity.[41] Collectively, the mechanistic diversity – encompassing cell wall disruption, protein denaturation, spore germination inhibition, and isothiocyanate-mediated DNA interference – establishes *M. oleifera* as a multi-target natural antimicrobial agent with substantial therapeutic potential across bacterial, fungal, and plant pathogenic infections.[7]

Antioxidant

M. oleifera is among the most potent plant-derived antioxidant sources documented in contemporary phytopharmacological literature, with bioactive constituents distributed across its leaves, seeds, roots, and pods demonstrating robust free radical-scavenging activity across multiple validated assay systems. Its flavonoids, phenolic acids, and vitamins exhibit potent free radical-scavenging activity and modulate key oxidative stress signaling pathways, including NF-κB and mitogen-activated protein kinase, establishing antioxidant activity as a mechanistic foundation underlying many of its broader pharmacological properties.[14] Both mature and tender leaves contain chlorogenic acid, rutin, quercetin glucoside, and kaempferol rhamnoglucoside polyphenolic constituents responsible for strong antioxidant activity and prevention of oxidative tissue damage.[19,42] Aqueous extracts of *M. oleifera* demonstrate effective free radical neutralization, with kaempferol – a flavonoid predominantly concentrated in the leaves – identified as the principal constituent responsible for this antioxidant capacity.[43] Furthermore, *M. oleifera* exhibits synergistic antioxidant protection when combined with piperine and curcumin, collectively attenuating beryllium-induced oxidative stress in Wistar rats – a finding that highlights its potential as a complementary agent in combination antioxidant therapy.

Anti-Inflammatory Effect

M. oleifera exerts well-documented anti-inflammatory activity through mechanistically distinct pathways that collectively suppress both enzymatic and cytokine-mediated inflammatory cascades. Quercetin and kaempferol inhibit the proinflammatory enzymes cyclooxygenase (COX) and lipoxygenase, while isothiocyanates modulate NF-κB signaling and suppress production of pro-inflammatory cytokines tumor necrosis factor-alpha (TNF-α) and interleukin-1 beta (IL-1β).[19] The anti-inflammatory activity of *M. oleifera* is mechanistically grounded in its capacity to suppress multiple convergent inflammatory pathways simultaneously – inhibiting NF-κB nuclear translocation, downregulating COX-2 expression, and attenuating proinflammatory cytokine production – thereby targeting inflammation at both the enzymatic and transcriptional level.[15,44] *M. oleifera* seed oil demonstrates clinically relevant anti-inflammatory activity in dermatological conditions, effectively reducing keratinocyte hyperproliferation and inflammatory mediator expression in animal models of eczema and psoriasis, establishing it as a viable topical alternative for inflammatory skin diseases.[45] Beyond dermatology, the combined anti-inflammatory and free radical-scavenging properties of *M. oleifera* address the pathological nexus between oxidative stress and chronic inflammation that underlies metabolic and neurological disorders. Preclinical evidence supports the beneficial effects of *M. oleifera* leaf extracts in combating the characteristic features of diabetes mellitus by targeting oxidative stress and inflammation as primary therapeutic endpoints – mechanisms particularly relevant given that hyperglycemia-induced ROS generation drives the inflammatory cascades that perpetuate insulin resistance.[46] Neuroinflammation and oxidative stress are pivotal drivers of neurodegenerative conditions, including Parkinson's disease, Alzheimer's disease, multiple sclerosis, and Huntington's disease, and the neuroprotective and anti-neuroinflammatory activities of *M. oleifera* have been documented across numerous studies, attributed to its richness in phytochemicals with antioxidant and anti-inflammatory properties.[47]

Antihypertensive

Hypertension is a leading modifiable cardiovascular risk factor affecting over 1.3 billion individuals globally, with disproportionate prevalence in low- and middle-income countries where access to conventional antihypertensive therapy remains limited – the same settings where *M. oleifera*

is most widely cultivated and consumed. *M. oleifera* leaves, seeds, flowers, roots, and pods are used in traditional medicine to treat hypertension, and preclinical evidence consistently attributes antihypertensive properties to the plant, particularly its leaves, through multiple mechanistic pathways.[48] *M. oleifera* leaves are particularly rich in bioactive compounds – including potassium, calcium, polyphenols, isothiocyanates, carotenoids, and tannins – that collectively underpin its antihypertensive activity through complementary vascular, antioxidant, and anti-inflammatory mechanisms.[49] Among the phytochemicals of *M. oleifera*, moringin – a stable isothiocyanate – demonstrates potent antihypertensive activity by functioning as a natural angiotensin-converting enzyme (ACE) inhibitor, blocking the conversion of angiotensin I to the vasoconstrictor angiotensin II and thereby facilitating vasodilation and systemic blood pressure reduction.[50,51]

Hepatoprotective and Nephroprotective Activities

The liver and kidneys are the primary organs of detoxification and metabolic regulation, rendering them highly vulnerable to oxidative stress, inflammation, and xenobiotic-induced injury – pathological processes that *M. oleifera* phytochemicals are uniquely positioned to counteract. Pharmacological studies confirm the hepatoprotective potential of *M. oleifera* extracts across multiple plant parts, with novel isolates including muramoside A and B and niazimin A and B identified as key contributors to its organ-protective and antioxidant effects.[32] *M. oleifera* exhibits nephroprotective potential in chronic kidney disease through phenolic compounds that confer antioxidant, anti-inflammatory, and anti-apoptotic benefits, while simultaneously demonstrating hepatoprotective effects against paracetamol-induced acute liver toxicity through antioxidant, tissue-protective, and immunomodulatory mechanisms.[8] The major pathological processes driving both hepatic and renal dysfunction – oxidative stress, inflammation, fibrosis, and apoptosis – are collectively modulated by *M. oleifera* isothiocyanates, flavonoids, and phenolic acids through activation of the Nrf2 cytoprotective pathway, regulation of inflammatory signaling, and enhancement of endogenous antioxidant enzyme activities, including superoxide dismutase (SOD), catalase, and glutathione.[52] Aqueous and alcoholic extracts of *M. oleifera* roots and flowers demonstrate significant hepatoprotective activity against acetaminophen-induced hepatotoxicity, evidenced by dose-dependent reductions in serum alanine aminotransferase (ALT), aspartate aminotransferase, alkaline phosphatase (ALP), and bilirubin – biochemical markers whose normalization collectively indicates attenuation of hepatocellular injury, cholestasis, and oxidative membrane damage through a multi-mechanistic organ-protective action.[7,53]

Antidiabetic

Diabetes mellitus is a chronic metabolic disorder characterised by persistent hyperglycemia arising from defective insulin secretion, impaired insulin signaling, or both – pathological conditions that *M. oleifera* phytochemicals address through multiple convergent molecular mechanisms. Preclinical evidence consistently supports the beneficial effects of *M. oleifera* leaf and seed extracts in combating the characteristic features of diabetes mellitus, encompassing effective blood glucose and insulin control, enhancement of insulin tissue sensitivity, improvement of blood lipid profiles, and protection against organ damage under sustained hyperglycemic conditions.[46] *M. oleifera* alleviates insulin resistance through dual pathway activation – stimulating the insulin-independent PI3K/AKT pathway and the AMP-activated protein kinase (AMPK) pathway in skeletal muscle – while simultaneously improving skeletal muscle oxidative metabolism through the Sirtuin 1–peroxisome proliferator-activated receptor (PPAR)-α pathway and enhancement of fatty acid peroxidation.[46] At the enzymatic level, quercetin activates AMPK, augments glucose uptake through GLUT4 stimulation in skeletal muscle, and suppresses hepatic glucose production through downregulation of phosphoenolpyruvate carboxykinase and glucose-6-phosphatase – key gluconeogenic enzymes whose inhibition mirrors the primary mechanism of the first-line antidiabetic drug metformin.[54] A systematic review and meta-analysis of 44 preclinical studies enrolling 699 diabetic rodents reported a pooled blood glucose reduction effect size of −3.92 (95% confidence interval: −4.65–−3.19) following *M. oleifera* extract administration, providing quantitative confirmation of its antihyperglycemic efficacy across diverse experimental diabetes models.[55] Collectively, the multi-target antidiabetic mechanism of *M. oleifera* – spanning insulin sensitization, glucose transporter upregulation, gluconeogenesis suppression, and oxidative stress attenuation – positions this plant as a scientifically validated natural adjunct in diabetes prevention and management.

Cardioprotective Activity

M. oleifera demonstrates well-documented cardioprotective activity through complementary antioxidant, anti-inflammatory, and vasoprotective mechanisms. Freeze-dried aqueous and alcoholic extracts confer significant protection against isoproterenol-induced myocardial infarction in animal models, evidenced by restoration of cardioprotective enzymes – SOD, catalase, glutathione peroxidase, lactate dehydrogenase, and creatine kinase – and attenuation of isoproterenol-induced hemodynamic dysfunction.[56] Butanolic extract additionally serves as a potent source of antioxidants in isoproterenol-induced cardiac necrosis models, while the compound N-α-rhamnopyranosylvincosamide significantly suppresses myocardial necrosis and inflammatory responses, identifying a specific molecular mediator of the cardioprotective effect.[57]

At the vascular level, *M. oleifera* leaf extract protects hypertensive rats against cholesterol elevation, an effect

attributed to the active thiocarbamate constituents niazirimin A, niazirimin B, and niazimicin.[58] Thiocarbamate compounds niazimin-A, niazicin-A, and niaziminin-B further exert potent antihypertensive activity through targeted ACE inhibition – the same mechanistic axis exploited by conventional antihypertensives – with protein–ligand docking studies confirming higher binding affinity for ACE than the reference drugs captopril and enalapril.[7,59]

Wound Healing Activity

Wound healing proceeds through four sequential phases – hemostasis, inflammation, proliferation, and tissue remodeling – each requiring precise coordination of cellular activity, growth factor signaling, and extracellular matrix deposition. A Preferred Reporting Items for Systematic reviews and Meta-Analyses-guided scoping review of 23 *in vivo* studies reported significant wound healing activity across all included studies, with *M. oleifera* aqueous leaf extract formulations consistently accelerating wound contraction, increasing epithelialization rate, and promoting collagen accumulation through combined antimicrobial, antioxidant, and anti-inflammatory mechanisms.[60] At the molecular level, quercetin, caffeic acid, and kaempferol demonstrate the highest binding affinity for wound healing-related proteins, transforming growth factor-beta 1, vascular endothelial growth factor, TNF-α, and IL-1β, collectively promoting angiogenesis, fibroblast proliferation, and collagen deposition while suppressing the inflammatory mediators that impede tissue repair.[61] In methicillin-resistant *S. aureus*-infected wound models, *M. oleifera* leaf extract simultaneously reduces microbial load, increases epidermal height, enhances angiogenesis, and promotes collagen deposition – demonstrating concurrent antimicrobial and tissue-regenerative activity of direct relevance to infected and chronic wound management.[62]

Hypocholesterolemic and Hypolipidemic Activities

Dyslipidemia – characterised by elevated total cholesterol, low-density lipoprotein (LDL), and triglycerides alongside reduced high-density lipoprotein – is a primary modifiable risk factor for cardiovascular disease, and *M. oleifera* demonstrates well-documented lipid-lowering activity through mechanistically diverse pathways. The ethanolic extract of *M. oleifera* suppresses HMG-CoA reductase activity – the rate-limiting enzyme of cholesterol biosynthesis – while β-sitosterol present in the leaves exerts documented cholesterol-lowering effects in high-fat-fed rats, and leaf saponins reduce cholesterol absorption by binding to cholesterol and bile acids, thereby diminishing enterohepatic bile acid circulation.[19] In diet-induced hypercholesterolemic rats, *M. oleifera* leaf powder at 0.737% and dry extract at 400 mg/kg body weight significantly attenuate high-fat diet-induced elevations in total cholesterol, triglycerides, LDL cholesterol, malondialdehyde, and hepatic transaminase activities – demonstrating simultaneous hypolipidemic and hepatoprotective effects.[63] At the transcriptional level, *M. oleifera* leaves prevent hepatic lipid accumulation by downregulating diglyceride acyltransferase-2 and *PPAR*-γ gene expression, while concurrently reducing hepatic concentrations of proinflammatory cytokines IL-1β and interferon-γ in a dose-dependent manner.[64] A systematic review of 108 non-clinical and clinical studies confirms that *M. oleifera* exerts its lipid-modulating effects through antioxidative and anti-inflammatory actions that collectively regulate glucose and lipid metabolism, preserve target organ integrity, and favorably modulate gut microbiota composition.[65] Collectively, the multi-target lipid-lowering mechanisms of *M. oleifera* – spanning cholesterol biosynthesis inhibition, intestinal absorption reduction, hepatic gene regulation, and gut microbiome modulation – establish its potential as a natural hypolipidemic agent complementary to conventional lipid-lowering therapy.[7]

ESTHETIC USE

M. oleifera has emerged as a high-value ingredient in cosmetic and dermatological formulations, driven by its exceptional concentration of skin-active phytochemicals across multiple plant parts. Its phytochemical profile – encompassing fatty acids, phenolic acids, sterols, tocopherols, carotenoids, and flavonoids – underpins a broad range of dermatological effects, establishing *M. oleifera* as a multifunctional cosmeceutical with documented applications in skin disease, wound healing, and anti-aging formulations.[66] Leaf extracts demonstrate particular promise as topical actives, with *M. oleifera* leaves being notably rich in α-tocopherol and other bioactives that protect against oxidative damage from ultraviolet (UV) radiation and environmental pollution – properties now being harnessed in advanced microencapsulated cosmetic formulations to enhance skin absorption and sustained delivery.[67] Collectively, the antioxidant potency, anti-inflammatory activity, and UV-protective capacity of *M. oleifera* extracts position this plant as a scientifically validated, sustainable alternative to synthetic actives in modern skincare.[66,67]

TOXICOLOGICAL ASPECTS AND SAFETY EVALUATION

Despite its extensive therapeutic applications, a rigorous evaluation of the toxicological profile and safety of *M. oleifera* is essential before its broader integration into clinical practice and nutraceutical formulations. Safety studies in animals involving aqueous leaf extracts indicate a high degree of safety, and no adverse effects have been reported in association with human studies, with leaf extracts demonstrating the greatest antioxidant activity alongside a favorable safety

profile across acute and subacute toxicity evaluations.[68] To date, no adverse effects of *M. oleifera* consumption based on human studies have been reported, and most in vitro studies involving normal human cell lines and cancerous cell lines confirm the safety of the plant at therapeutic concentrations, with safety maintained even at doses of 2000 mg/kg in animal models.[33] However, dose-dependent safety concerns have been documented with specific plant parts and preparations. At high doses, *M. oleifera* exhibits severe toxic and abortifacient effects, with root bark preparations in particular containing thiocarbamate glycosides – including moringinine – that demonstrate uterotonic activity, rendering their use contraindicated in pregnancy.[32] Subacute toxicity studies of leaf extract at doses ranging from 40 to 1000 mg/kg reveal transient elevations in liver enzymes ALT and ALP alongside reduced creatinine levels, though without corresponding adverse histopathological findings – suggesting biochemical adaptation rather than overt hepatotoxicity at therapeutic dose ranges.[69]

Clinically significant drug interactions represent an underinvestigated but important safety consideration. *M. oleifera* extracts inhibit cytochrome P450 enzymes – specifically CYP3A4, CYP1A2, and CYP2D6 – in laboratory studies, raising the potential for pharmacokinetic interactions with co-administered drugs metabolized through these hepatic pathways, including lovastatin, certain antifungals, and antiretroviral agents. Additive hypoglycemic effects with insulin and sulfonylureas, potentiation of antihypertensive medications, and possible interference with levothyroxine conversion from thyroxine to triiodothyronine have all been identified as priority drug interaction concerns warranting clinical vigilance.[70] The pharmacological safety of *M. oleifera* requires nuanced understanding, as its therapeutic benefits must be balanced against dose-dependent risks, plant part specificity, and the absence of standardised extract formulations validated through rigorous clinical trials.[71] Collectively, while the general safety profile of *M. oleifera* leaf preparations at therapeutic doses is well supported, the absence of long-term human safety data, standardised dosing guidelines, and systematic drug interaction studies represents a critical gap that must be addressed before its widespread clinical application can be recommended.

FUTURE PERSPECTIVE AND RESEARCH GAPS

Despite its well-documented pharmacological and nutritional benefits, the clinical and industrial application of *M. oleifera* remains limited due to several key challenges. A major concern is the lack of standardization in extraction methods and phytochemical composition, leading to variability in reported outcomes.[27] In addition, most evidence is derived from preclinical studies, highlighting the need for well-designed human clinical trials to establish efficacy, safety, and optimal dosage. The bioavailability and pharmacokinetics of its bioactive compounds are not fully understood, which may limit therapeutic effectiveness. Furthermore, comprehensive data on long-term toxicity and safety are still insufficient.[19] At the molecular level, the precise mechanisms underlying its diverse biological activities require further elucidation through advanced approaches such as omics technologies. Future research should also focus on improving formulation strategies for functional foods, enhancing genetic and agronomic traits, and exploring novel industrial applications. Addressing these gaps will be essential to translate *M. oleifera* from a traditional remedy into an evidence-based therapeutic and nutraceutical resource.

CONCLUSION

M. oleifera has emerged as a multifunctional plant with significant pharmacological, nutritional, and therapeutic potential, largely attributed to its diverse bioactive constituents. Although substantial preclinical evidence supports its efficacy in managing various diseases, its translation into clinical practice remains limited due to challenges such as a lack of standardization, insufficient human studies, and unclear pharmacokinetic profiles. Addressing these limitations through rigorous clinical trials, advanced mechanistic studies, and innovative delivery systems will be essential. With continued interdisciplinary research, *M. oleifera* holds strong promise as a sustainable and evidence-based candidate for future nutraceutical and pharmaceutical development.

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